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Accuracy in setting-out

The growth of partial or complete prefabrication of building structures places greater emphasis than ever before on the need to attain predictable standards of accuracy in the setting-out and erection processes. The degree of accuracy which can be achieved in construction has a significant bearing on design: in extreme cases, the feasibility of a structural system may depend on the standard of site accuracy that can be safely assumed.

This digest concentrates on accuracy in the setting-out process, which BRE studies have shown to be critical for the avoidance of subsequent problems during erection. The data included should assist constructors in choosing the techniques necessary to attain the specified accuracy in setting-out, and designers by showing the level of accuracy to be expected in given circumstances. It should be read in conjunction with Digest 202 which recommends procedures which will control inaccuracy in the site use of theodolites and surveyor's levels, and it replaces Digest 114 which is now withdrawn.

What determines accuracy in setting-out?

Ultimately, the standard achieved in setting-out depends on the accuracy of:

- Linear measurements
- Establishing and transferring horizontal levels
- Establishing and transferring verticals
- Delineating angles
- Delineating straight lines.

For each of these operations, a variety of methods may be used, depending on type of site, type of structure, the requisite degree of accuracy, and to a limited extent personal preference.

Accuracy in linear measurement

Given a tape measure, few would doubt their ability to measure distances with precision, but in practice serious errors occur. Studies have shown that, even with experienced site personnel, errors of 25mm in a

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taping length of 30m are possible when using steel tapes. Errors with fabric-based tapes are potentially very much greater and the use of fabric tapes cannot be recommended for any setting-out process. Taping errors may arise in any of the following ways:

Reading errors are closely allied to the quality and fineness of tape graduation; with most tapes they are unlikely to be significant when compared with other sources of error. Metric tapes to BS 4484: Part 1: 1969 are graduated in units of 5 mm, except at beginning and end, where 1 mm divisions appear. The 5 mm divisions may be subdivided by eye; the reading error should not exceed 2 mm.

Calibration errors BS 4035 required that tape graduations be correct to within $\pm 1/16$ in (=1.5 mm). Although, as far as is known, no tapes were specifically manufactured to this standard, calibration errors can be ignored if reputable steel tapes, in good condition, are used. Random checks have shown that errors are unlikely to exceed 3 mm at any point marked on the tape. BS 4484: Part 2 will specify an appropriate graduation accuracy for metric tapes and it is hoped that tapes will be available to meet this standard.

Tension errors are the largest source of error in taping. Steel tapes normally available for use on site are graduated fully supported and at a constant tension of 44.5 N (equivalent to a pull of 4.5 kg on a tension balance). Site studies showed that a range of 9 N to 175 N might be applied in practice to a 10 mm wide tape fully supported, resulting in errors of up to 10 mm in a 30 m measurement; in catenary measurements an even greater range of tension was used, from 10 N to 330 N. Tension control is therefore essential if accurate measurements are to be made. For accurate measurements made with the tape fully supported this tension should be the calibration tension of the tape, usually 4.5 kg on a spring balance.

Tape sag Wherever a tape is unsupported, it sags into a catenary between the two ends. Because the length of the arc is greater than the length of the chord, which is the distance to be measured, the sag effect will cause an over-estimate of the distance. In practice, however, the reverse may be true since some operators faced with a sagging tape try hard to eliminate the sag by increasing the tape tension to the extent that the effect of stretch predominates. For accurate measurement in catenary, the calibration tension should be applied and the manufacturer's recommended correction for catenary applied. An alternative, simpler, procedure which produces a satisfactory level of accuracy for most building applications is to make use of the tensile stretch of the tape to offset the error caused by the sag. For a given tape cross-section, there is a single compromise tension at which the amount of stretch will nearly compensate for sag when the tape is in a catenary and which will give similarly close accuracy if the tape is fully supported. The appropriate tensions for etched tapes of standard thickness* are 70 N for a 10 mm wide tape and 105 N for a 13 mm wide tape (7.1 kg and 10.7 kg respectively on a tension balance). Table 1 shows the errors arising when tapes are used in a variety of conditions, i.e. fully supported and in catenary, with and without control of tension; it shows the improved overall accuracy obtained by the use of compromise tensions.

* Heavily chrome-plated tapes and other abnormally thick tapes will require greater tension.

5 in 100
4 in 100
3 in 100
2 in 100
1 in 100
1 in 20
1 in 30
1 in 40
1 in 50
1 in 60
1 in 80
1 in 100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14mm
corrections to be added to horizontal dimensions to obtain dimensions on slope

Fig 1 Correction for slope (per 10m measured)

Table 1 Steel tapes: combined effect of tension and catenary errors

Maximum likely errors, in mm, in setting out a distance of 30 m in a single measurement.
(Errors for shorter distances always less.)

	10 mm wide tape		13 mm wide tape	
Applied tension	Tape fully supported	Tape in catenary	Tape fully supported	Tape in catenary
Range observed in site experiments	−3 to +10	−13 to +15	−2 to +7	−20 to +12
44.5 N (calibration tension)	0	−12	0	−28
70 N (compromise tension for 10 mm tape)	+2	−3	–	–
105 N (compromise tension for 13 mm tape)	–	–	+3	−3

Differences in level between measured points cause errors which are significant even on quite gentle slopes. Over short distances, these can usually be corrected by holding the tape approximately horizontal but over greater distances more accurate results will be obtained by measuring on the slope and applying the appropriate correction taken from Fig. 1.

Thermal movement can cause significant errors in very hot or cold conditions. Tapes are normally calibrated at 20° C and corrections should be made for any considerable departure from this temperature. In dull weather, air temperature is a reliable guide to tape temperature but in bright sunshine tapes - particularly dark coloured ones - quickly reach temperatures above the local shade temperature. When a tape is used in catenary, the effect of this is only marginal: generally the tape will reach only about 5° C above local shade temperature. On a flat surface, however, an excessively high temperature may be reached, dependent on the temperature of the surface. In such a situation, the effect can be largely eliminated by raising the tape on small wooden blocks to allow some air circulation around it. When the tape temperature is higher than the calibration temperature of 20° C, 1 mm in 10 m should be deducted from the tape reading for every 10° C difference; when the tape temperature is below calibration temperature, an equivalent addition should be made. When measuring existing work, the correction will have the opposite sign.

Accurate taping procedure

If no correction is made to tape measurements other than for slope, the maximum likely error is about 25 mm in a 30 m length, and there is a fair probability of an error of 15 mm. For closer accuracy, further corrections must be applied. For most purposes, use of the appropriate compromise tape tension will bring the accuracy up to the required standard, but for the most accurate work correction for tape temperature may be necessary if the ambient temperature is markedly different from 20° C. With all corrections applied, and the appropriate compromise tension in use, measurements should be accurate to within ±6 mm in a 30 m length, with smaller errors at shorter distances.
To achieve this standard:

1 Use a tape in good condition
2 Check ring fixing at start of tape to identify zero of graduations (practices differ between makers).
3 Estimate tape temperature, and apply correction if necessary.
4 Estimate or measure slope and apply correction if necessary. (Fig 1)
5 Apply appropriate compromise tension.
6 Read tape to nearest mm, subdividing the 5 mm graduations by eye and avoiding parallax as far as possible.

Tension control The usual way of applying tension is through a spring balance, of which some designs (Fig 2) have a device for quick attachment to the tape. Skill is needed to apply the correct tension and to read the tape and spring balance simultaneously.

Electronic distance measuring devices
Whilst more common on big civil engineering projects, these devices are being used increasingly by land surveyors to establish primary points and may be used on large sites to check primary setting out. They are not suitable for general setting out or for short range work of less than 50 m.

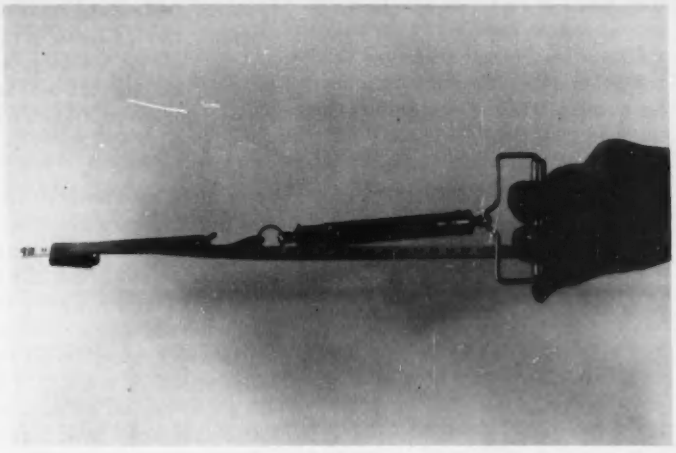

Fig 2 Tension applied through spring balance

Accuracy in horizontal level

The accuracy achieved in establishing and transferring levels depends on the quality and condition of the instruments and on the skill of the operatives. Table 2 lists the more usual instruments used in site work, and gives an estimate, based on BRE measurement surveys, of the accuracy which is likely to be achieved in practice with instruments in good condition, and operatives of average competence. The best equipment used with care and skill, is capable of greater accuracy.
Several models of laser are available for establishing alignment and some project a rotating beam to define a horizontal or vertical plane; unlike optical instruments they can be used to define points simultaneously on different parts of the site. Lasers are comparatively new and are at present unlikely to be suitably robust or reliable for use on building sites.

Checking optical levels It is dangerous to assume that because an expensive optical level is being used it will necessarily give the accuracy indicated in Table 2. A survey of optical levels in use on sites showed 1 in 10 to be seriously out of adjustment, one being no less than 75 mm out in a sight of 30 m. All optical levels should therefore be checked regularly and adjusted when necessary. Trained surveyors know and observe such routines as a matter of course, but much setting-out on sites is necessarily in the hands of people who have had little or no formal training in surveying. A simple check is described in Digest 202.

Errors in staff reading With the introduction of the metric staff, to BS 4484; Part 1: 1969, errors in staff reading should be minimised. The staff is graduated in 10 mm intervals and test experience has shown that

Table 2 Horizontal Level

Method	Probable accuracy	Suggested useful range	Comments
Water level	±5 mm independent of distance	Limited to length of tube supplied–generally <15 m	Sensitive to temperature. Useful for transferring levels quickly round corners
Light self-levelling level	±8 mm in 30 m	30 m per sight	Particularly easy to use, giving adequate accuracy for much building work: with attachments, can be used to set out standard falls
Optical levels	±5 mm to ±2 mm per single sight, depending on quality of instrument	Up to 60 m	Universal in application, for all precise work. Some types can set out falls

these can generally be subdivided by eye to the nearest 2 mm. For closer accuracy, rarely needed in building work, a parallel plate micrometer may be used for precise subdivision of the scale.
The staff used with the light self-levelling level is intended to be read by the staff man and the figuring should, preferably, be similar to that on an ordinary rule.

Precautions with water levels Theoretically, water levels are very accurate, but in practice errors can arise if the two vertical arms of the water tube are at different temperatures. The difference between sun and shade temperatures can give rise to significant differences in the levels of the liquid in the two arms: the error will be shown up by an inability to obtain the same level when the two arms are compared side by side. A similar effect occurs if any air is present in the water. Before using water levels, therefore, check that the levels in the two arms are indeed the same and that no bubbles are present in the filling water. Keep the instrument out of direct sunlight except when actually being used.

Accuracy in verticals
The range of instruments available for checking and transferring verticals is less comprehensive than for levelling. Those instruments available, and the accuracy it is reasonable to expect from them, are given in Table 3. Until recently, there was a gap between the capabilities of the plumb-bob and those of the theodolite, or specialised optical plumbing instrument, but this gap has been filled by a light self-levelling optical plumb using the principle of coincidence of a split image. This is a significant addition to the range because plumb-bobs have severe limitations in windy conditions, yet on many sites the use of the highest precision instruments is not warranted nor is the experienced staff available to ensure their correct use.

Accuracy in angular measurements

Methods of setting out angles are listed in Table 4, with an estimate of probable accuracy.

Using steel tapes Taping methods are most suitable for use on terrain which is relatively flat, and where there is no need to project the angles

Table 3 Verticality

Method	Probable accuracy	Suggested maximum range	Comment
Builder's spirit-level	±7 mm in 3 m	3 m	Craftsman's tool, only suitable for rough work up to storey height: unsuitable if component edge is bowed
Plumb-bob	±5 mm in 3 m	3 m	Suitable for general work up to storey height, in still weather
Plumb-bob, heavy, immersed in oil to damp movement	±5 mm in 10 m	10 m	May be used over greater heights in totally wind-free conditions
Light, self-levelling optical plumb	±6 mm in 15 m	15 m	Used as a conventional optical plumb or in the hand against walls
Theodolite (graduated to 20 sec. with diagonal eyepiece)	±5 mm in 50 m	50 m	For multi-storey work. Range limited by visibility of target: tall buildings may be plumbed in two or more stages
Theodolite (graduated to 1 sec. with diagonal eyepiece)	±5 mm in 100 m	100 m	
Optical plumbing device	up to ±5 mm in 100 m	100 m	Comments as for theodolite. Range of instruments available with different standards of accuracy

into trenches, etc. Theoretically, any angle can be set out by using steel tapes to construct triangles in which the three sides sides bear the appropriate ratios. In practice, only 90° angles are normally set out in this way, using a triangle with sides in the ratio 3:4:5; because the three sides are not very different in length, taping errors tend partially to cancel out and the degree of accuracy obtained is quite high. Corrections must always be made for sloping ground; accuracy will be further improved if all taping corrections are applied and if the tape tension is controlled as described earlier (see Table 4).

Using optical instruments For setting out right-angles, an inexpensive tripod-mounted optical square is available. It consists of two small telescopes, the axes of which are at 90° to each other and which can be swivelled in a vertical plane, along with means for centring over a reference point. The instrument can be used equally well on flat or sloping ground, and can project angles into trenches. It gives an accuracy comparable to that obtainable with steel tapes. Optical limitations make sighting over distances in excess of 30 m difficult, and in poor lighting conditions sights of not more than 15 m are preferable. Theodolites provide a higher standard of accuracy - largely determined by their fineness of calibration - and their superior optics enable angles to be projected distances in excess of 50 m; furthermore, any desired angle can be set out. Theodolites calibrated to 20 seconds should be adequate for most site work, but should for preference be fitted with optical plummets; plumb-bobs are a significant source of error in windy conditions. One-second theodolites - which are normally fitted with optical plummets - offer greater accuracy for critical work.

Straightness of line

Where a theodolite is available, there is no difficulty in delineating any required line on site, and in fixing any desired number of intervening points, but on the majority of sites only tapes and levels are available and lines are set out by stretching builders' twine between established points. Tests have shown that even a modest breeze produces sufficient sideways bowing in the twine to introduce serious errors and if enough tension is applied to eliminate most of the catenary the twine may break or a holding peg may be displaced. Better results are obtained with synthetic lines (polypropylene stranded twine has been used) which being stronger can be used much thinner, thus requiring less tension to eliminate the wind error.

Table 4 Setting out angles

Method	Angle	Probable accuracy		Suggested useful range	Comments
Steel tape	Generally 90° (using 3:4:5 triangle)	Corrected for slope only:	±15 mm in 30 m	30 m	Unsuitable for uneven terrain, or setting angles in trenches
		with all corrections and tension control:	±6 mm in 30 m		
Tripod-mounted optical sqaure	90° only		±10 mm in 15 m	15 m in all conditions 30 m in good light	Useful on uneven ground, and in trench work. Quick and simple to use
Vernier theodolite graduated to 20 sec; plumb-bob	Any	±40 sec.	(±10 mm in 50 m)	In excess of 50 m	Universal instruments. Precision depends mainly on fineness of calibration. Optical plummet an advantage in windy conditions
Glass arc theodolite graduated to 20 sec; optical plummet	Any	±20 sec.	(±5 mm in 50 m)	In excess of 50 m	
Glass arc theodolite graduated to 1 sec; optical plummet	Any	±5 sec.	(±2 mm in 80 m)	In excess of 50 m	

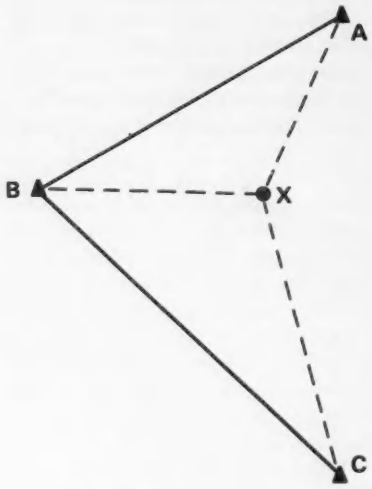

Fig 3 Setting-out by angular co-ordinates

Setting-out large or complicated site plans

For large or complex developments, an alternative to the traditional tape and theodolite methods of setting out plans, road alignments, drainage intersections, etc., is the use of angular co-ordinates provided by two theodolites to locate each desired point. Accuracy is improved and cost may be significantly reduced, but knowledge and skill are necessary. Figure 3 shows three permanent survey stations, A B,C, which are first established on the site and accurately surveyed. Then, in order to establish the position of any desired point X, visible from all three stations, angular co-ordinates XAB, ABX, XBC, BCX, are calculated - usually by computer; the point X is set out using, for example, co-ordinates XAB and ABX, and checked by reference to XBC and BCX. In practice, more than three stations will normally be required in order that all the desired points are visible from at least three stations. If care is taken in siting the stations so as to ensure that they are not disturbed during construction, points can be rapidly checked at any time. The accuracy achieved depends on the quality of theodolites used and on the competence of the operators.

Use of grids in setting-out building plans

Where the design of the structure has been based on a grid, use of a matching site grid will minimise errors, but it is essential that the site grid be established with sufficient accuracy. Careful use of steel tapes, following the principles outlined earlier, can establish grids without any use of optical devices, though on sloping ground fewer errors will arise if optical instruments are used. The best instrument for setting out large building plans is the theodolite, since it can project grid lines and angles accurately over considerable distances: furthermore, it can be used to check perimeter grid measurements by projecting measurements from one side of the site over to the other. If the working grid is relatively closely spaced, errors in location of structural elements are further reduced because offsets are smaller.

British Standards

BS 4035:1966 Linear measuring instruments for use on building and civil engineering constructional works. Steel measuring tapes, steel bands and retractable steel pocket rules

BS 4484: Measuring instruments for constructional works. Part 1: 1969 Metric graduation and figuring of instruments for linear measurement

BS 5606: 1978 Code of Practice for Accuracy in building

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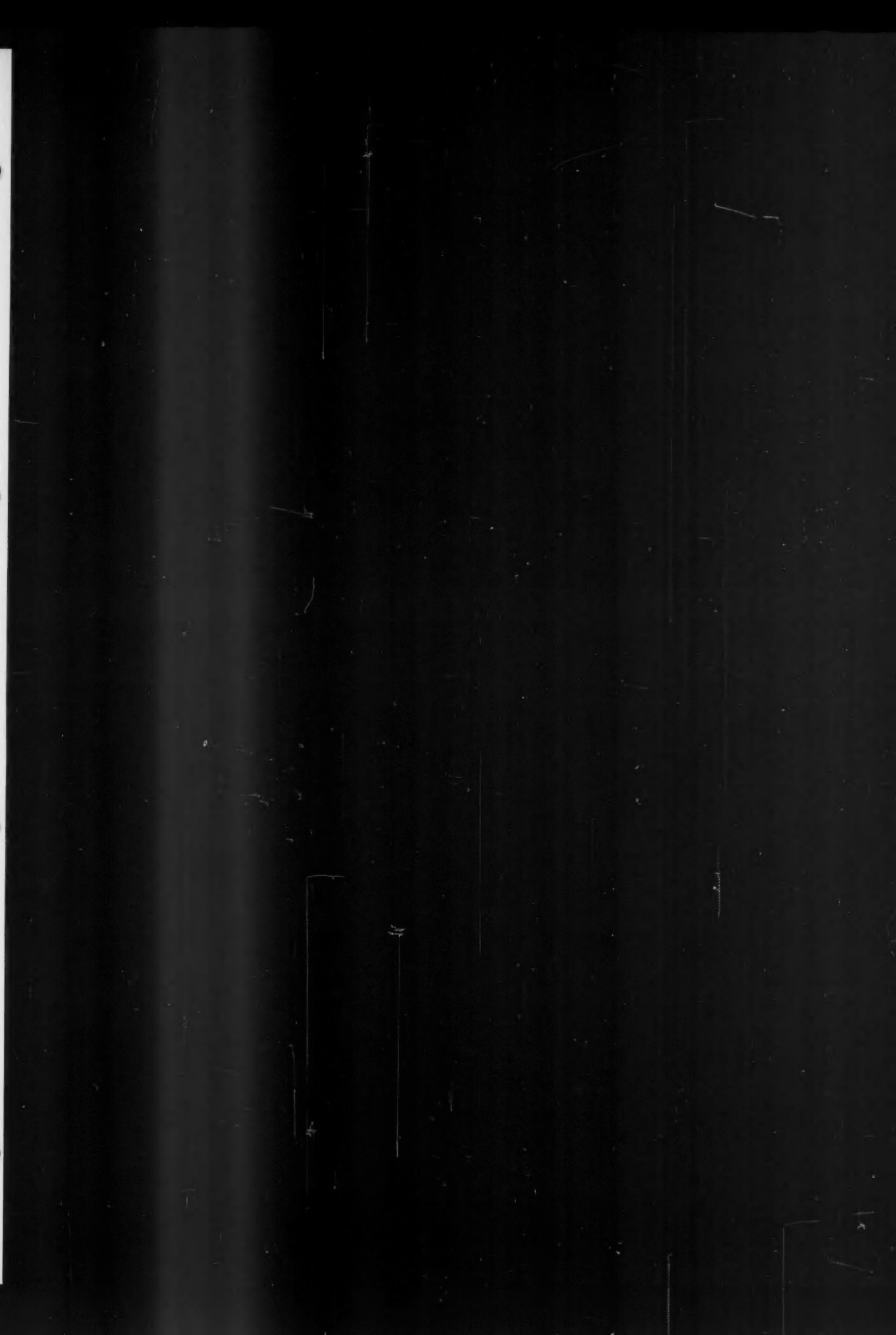
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